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Final Technical Report
July 1976

IMPROVED IMAGE PROCESSING

Columbia University

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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The design and evaluation of a unique electro-optical image processing system is discussed. The system simulates the compensatory mechanisms of the human visual system. The goal of the processing is the improvement of resolution in images degraded by Linear motion blur, defocus and diffraction.

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SUMMARY

An electronic processing system was designed to implement the technique of simulating the compensatory mechanisms of the human visual system which serve to improve image detail. The state of the art of available hardware was investigated and various components were selected and procured. The circuitry for interfacing the components and programming the sequence of processing was designed. The finished system is shown in Fig. 1. The components are numbered for identification in Section 3 to follow.

The input device is a high resolution video camera. There are three storage devices -- two scan conversion memories and a disc recorder. The processing is achieved by manipulating the image with a circular scan modulating the conventional deflection ramps, by offsetting and/or integrating and subtracting images. Fig. 2 shows the general flow of the video signal through the various components. Fig. 3 shows the general flow of the deflection signal and how it is modulated to effect a circular scan.

Candidate images were produced for processing in a photography phase of the program. Some of these were selected for processing and the improvements in resolution are shown. Recommendations for the continuation of this effort include modification of the equipment to lessen the noise in the system, augmentation of the system with a controller to reduce the operational time and maintain stability of the system, and further studies for optimization of parameters.

PREFACE

The purpose of this effort was to contribute to the art and science of image processing by employing a novel approach. The general objective was to develop a prototype system to process images degraded by linear motion blur, defocus and/or diffraction.

The technique is based on simulating what are believed to be physiological compensatory mechanisms of the human visual system (nutation) and is described in the interim report[1]. The interim report shows the mathematical formulations which serve as the basis for processing and the general processing techniques for each of the degradations. The implementation of these methods was the goal of the engineering design of the prototype system developed in this effort.

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[1]M.M. Kaplan, P. Diament and J.H. Troll, *Improved Image Processing*, RADC-TR-75-48, Interim Report (1975). AD# A007787.

EVALUATION

This investigation was conducted under Project 5534, "Special Purpose Sensing Techniques" (TPO-2). This effort was performed to develop a technique which would permit relatively simple and inexpensive improvement of degraded images.

The use of a technique based on the compensatory mechanisms of the human visual system to improve degraded images was shown theoretically feasible and was documented in RADC-TR-75-48, "Improved Image Processing." This report describes the experimental equipment that was fabricated to evaluate the potential of the technique. Results indicate that significant instrumentation changes are required before practical application of the technique can be made.

Melvin G. Manor, Jr.

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Project Engineer

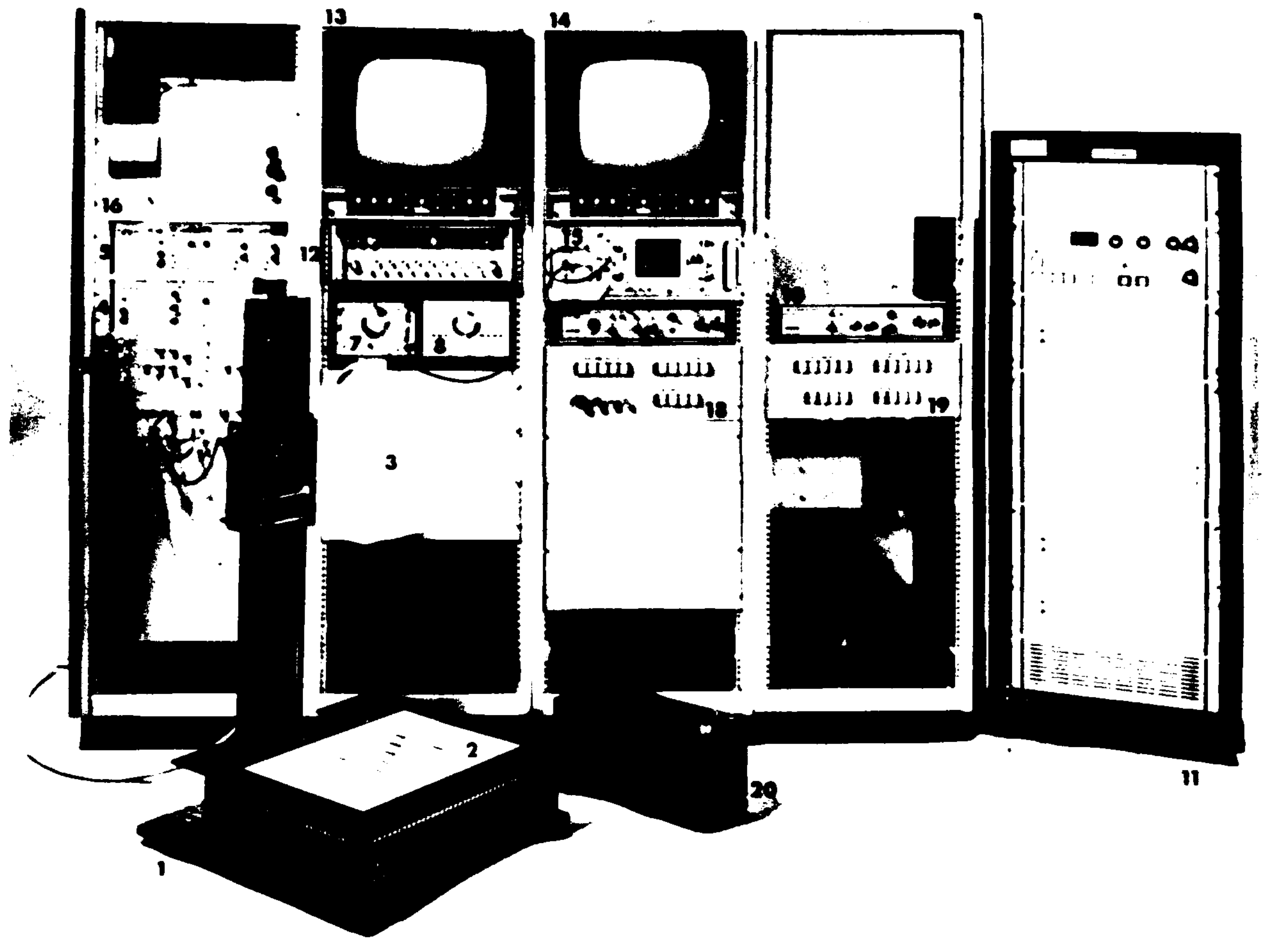

Figure 1. Prototype image processing system.

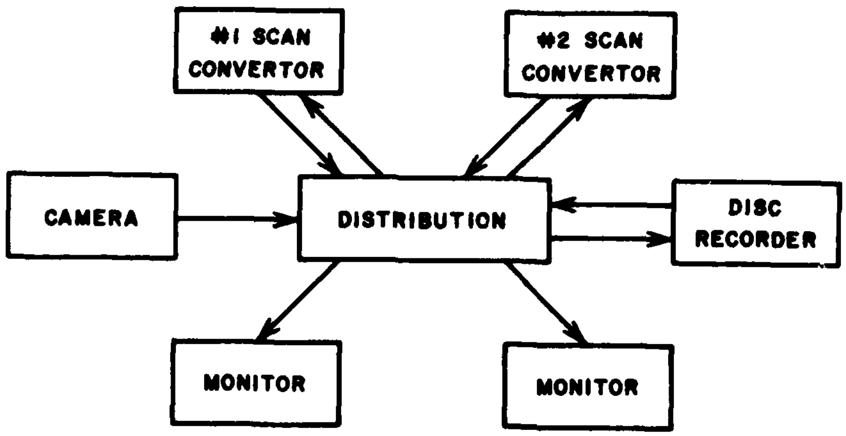

Figure 2. Simplified flow diagram of video information.

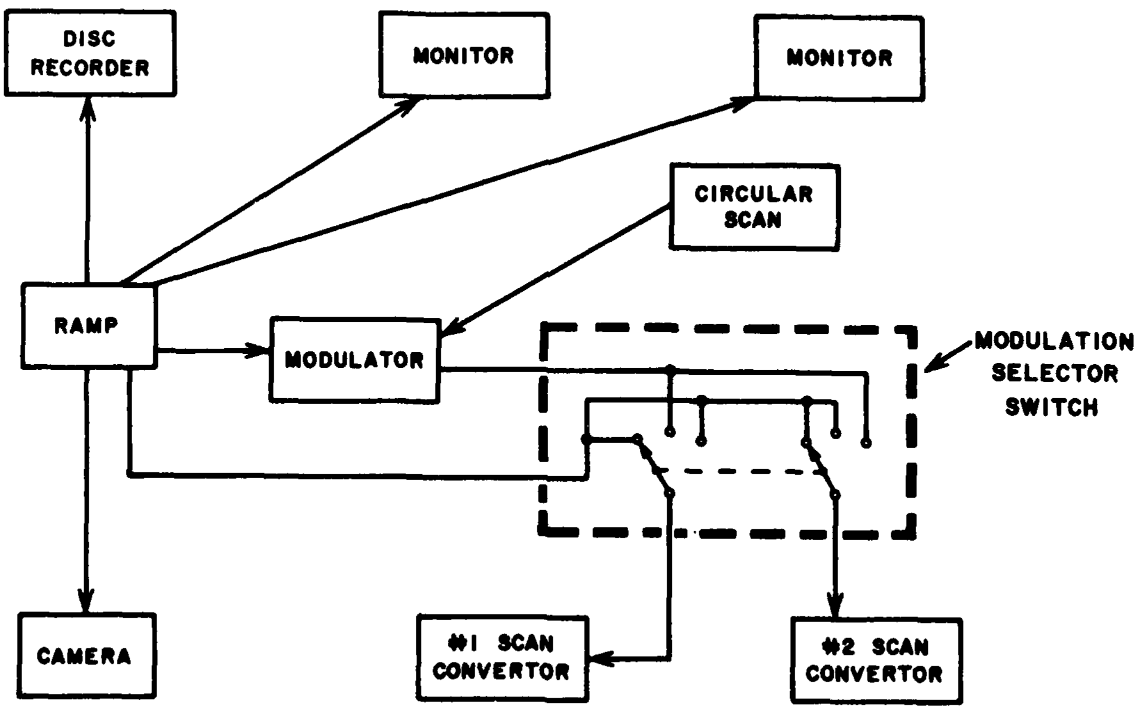

Figure 3. Simplified flow diagram of deflection signals.

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1. *PHOTOGRAPHY*

1.1. EQUIPMENT, MATERIAL AND CALIBRATION

The purpose of the photography program was the production of degraded images for processing and also clear reference images of the same target or event for comparison. The photography equipment components were variously arranged for the several series of exposures (see Appendix A, 1.1 - 1.9). Kodak High Contrast Copy film was employed for most exposures because of its fine grain. Kodak Panatomic X film was used where a higher ASA speed was necessary.

The first objective was the selection of the optimum developer for the Kodak High Contrast Copy film. Of the six evaluated, the Simple Pota process (see Appendix A, 2.2.2) was selected. The best results were obtained at 65°F. for 14 minutes, using an ASA speed setting of 12. The subject of the test exposures was the U.S. Air Force tri-bar resolution target in an outdoor garden background. The criteria for selection were the dynamic range and resolution of the images.

The next objective was the determination of the optimum focus setting with target-film plane separations of 500 ft., 150 ft. and 70 ft., respectively, using the 50-300mm f/4.5 Zoom Nikkor Auto lens. All the designated focal lengths were employed. These included: 50, 60, 70, 85, 105, 135, 200, 250, and 300 millimeters.

At the 500 ft. target-film plane separation, the resolution was best at the shorter focal lengths, but at 150 ft. and 70 ft. the resolution was better at the longer focal lengths.

1.2. IMAGES

1.2.1. Resolution Target

The production of resolution target images limited by each of three degradations was the object of this portion of the program: (1) defocus, (2) linear motion blur and (3) diffraction.

1.2.1.1. Defocus

The U.S. Air Force 1951 tri-bar resolution target was the subject of this series of exposures. The target-film plane separation was 10 feet for all exposures. The first image was made with the camera clearly focused. The next was made with the camera focused for a distance of 9 ft. 9 in. Each of the subsequent exposures was made with the camera focus successively changed by focusing for 3 in. closer, up to and including a distance of 1 ft. 3 in.

1.2.1.2. Linear Motion Blur

Photographic prints of the U.S. Air Force resolution target were the subjects of this series of exposures. The motion was achieved by employing a motion table. The calibrations for the motion and a description of the table and its operation may be found in Appendix B. The procedures described resulted in the production of 36 images, each with a different element motion-blurred to its zero crossing level.

1.2.1.3. Diffraction

A specially designed radial resolution target was the subject of the diffraction limited images. The diffraction blur was maximized by employing the smallest f/stop, and using Kodak High Speed Infrared film and an 89B filter so as to eliminate wave lengths under 680 nanometers. A series of images was produced to vary the spatial frequencies of the target bars by increasing the target-film plane separation from 10 ft. to 40 ft. in increments of 1 ft.

1.2.2. Others

Other images were produced at various sites to serve as candidates for subsequent processing. The range of degradation ran from blur lengths or diameters the equivalent of zero crossing element 6 of group -1 of the Air Force resolution target up to and beyond that of element 1 of group -6. These were exposed prior to the fabrication of the electronic processing system and with no knowledge of the system's capabilities. The highly degraded images proved to lack the contrast for any meaningful improvement by the system and the small degradations were beyond the resolution limits of the system.

The capabilities of the electronic system to process images can only be defined in terms of spatial frequency where the cycle width is related to raster size. Within this framework, the system operates most efficiently in processing images with blur lengths or diameters from group -4 to group -6 of the tri-bar Air Force target, where the target fills the entire raster. Smaller or larger blur lengths can be processed by zooming up or down so as to maintain this relationship between blur length and raster size.

2. *SYSTEMS DESIGN CONSIDERATIONS*

2.1. INTRODUCTION

This section is devoted to the considerations and design of an electronic system to rapidly process images by the techniques described in the Interim Report of this program. A key feature of this system, in addition to processing speed, is the adjustability of the processing parameters for various types and degrees of blur. The prescribed goals include processing images degraded by linear motion blur, defocus and diffraction. Each of these is an isoplanatic degradation where the point spread function does not vary throughout the image field.

The equipment is designed to scan an image, and nutate the image in various amplitudes. Nutation has been defined as the relative motion of two parallel planes whose coordinates remain parallel. It is also designed to add and subtract images and to repeat this processing in cycles. It has a storage capacity for a library of images and two monitors for comparison of images.

A survey of the state of the art of image processing revealed a number of electronic techniques that could be adapted to process images by the methods described in Section 1 of the Interim Report. Various components were studied for their respective capabilities and versatility in performing individual and combined functions in the processing. Balancing all the forseeable factors in combining these components finally led to the functional design of a system.

The system is designed to operate at the threshold of the state of the art of readily available components. At this threshold there are various trade-offs in processing parameters. In addition, there are a number of processing options. All these trade-offs and options have been taken into consideration in the systems design so as to provide a high degree of versatility.

These considerations will be examined in the body of this section, and the overall system will be described in Section 3, Final Design.

2.2. PROCESSING STEPS

2.2.1. Nutation

Two forms of nutation are employed in this project: linear nutation, for processing linear motion blur; and circular nutation, for processing defocus and diffraction blurs.

Linear nutation consists of superimposing two identical images that are displaced from one another, adding their illuminances and normalizing by dividing by 2.

Circular nutation must be examined before its implementation is described. Nutation, by definition for this processing, consists of the relative motion of two parallel planes whose corresponding coordinates remain parallel. Circular nutation defines this relative motion as being circular. This dictates that for any point on one plane there is a corresponding circle on the other and vice versa. Therefore, the nutation of an image can be achieved by forming and superimposing circles, the center of each circle in the nutated image corresponding to the location of a point in the original image and the total illuminance of each circle in the nutated image equal to that of its corresponding point in the original image. It can also be achieved by scanning circles in the original image and integrating them into points. Each point thus formed in the nutated image corresponds in location to the center of its corresponding circle in the original image, and the illuminance of each point corresponds to the integration of the illuminance of its corresponding circle.

The nutation can also be performed by sampling points in each of the circles as described. Of course, this technique is an approximation; the larger the sampling, the greater the accuracy. This sampling can be achieved by the superimposition of n identical images that are displaced in a circular locus, the addition of their illuminances and normalization by dividing by n. However, the sampling technique limits the effectiveness of nutation unless n is infinite.

2.2.1.1. Mechanical

A mechanical method of nutation was employed in the early experiments leading to this process and is described in the patent[2]. This and other mechanical methods were rejected for ultimate application because of tolerance requirements, mechanical adjustments necessary to change parameters, and low speed.

2.2.1.2. Optical

Any standard optical system may be modified to produce nutation by merely placing a mask at the second nodal plane.

In the case of circular nutation, the mask is a round opaque disc, smaller in diameter than the pupil of the lens system, so

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[2] M.M. Kaplan, *Image Reconstitution System*, U.S. Patent No. 3,713,730 (1973).

that the entering rays pass through an annulus. Assuming a perfect optical system, there is a point-by-point correspondence between object and image. However, if either the object or image plane is displaced, fore or aft, a point in the object plane corresponds to a circle or annulus in the image and vice versa. This fulfills the function of nutation. Other masks can provide other nutations. The radius of nutation, in this case, is a function of the displacement of either plane.

This method of nutation was used in a series of experiments prior to this project. While producing better results than the mechanical method, the optical system required mechanical adjustments to change parameters and there were alignment problems. It was rejected because of the necessity for these adjustments in processing any single image and the number of lenses that would have to be designed and produced for repeated cycling and versatility of processing.

2.2.1.3. Opto-Mechanical

Nutation can also be produced by rotating a prism between the object and image planes. The radius of nutation is determined by the power of the prism and/or the distance between the prism and the image plane. Varying the nutation radius requires fore and aft mechanical shifts of the object or image plane for processing one image or changing the prism power. Even if a Risley prism is used (two prisms, face-to-face, where the total prism power may be varied by changing their relative orientation), resetting the orientation two or more times is necessary in processing one image. In either case the prisms have to be mechanically rotated to produce the nutation.

2.2.1.4. Computer

This processing technique was also performed by computer digital manipulation in a feasibility experiment preceding this project. Despite the speed of the computer, it took many minutes for the double conversion (analog to digital and back to analog) and processing in one meridian for a 400x400 array. One can calculate the additional time required for the computer to process a 2100x1600 array in all meridians, plus the double conversion. This array represents the approximate number of picture elements in a 2100-line video frame, which is the input of the experimental system described in this report.

2.2.1.5. Electronic

Electronic nutation may be performed by manipulating either the write (input) image or the read (output) image. In order to avoid confusion in terminology, it may be parenthetically pointed out that in many computer languages "read" statements refer to input and "write" statements to output. The reverse is true in electronic scanning terminology. The electronics usage of these terms will be employed in this report. "Write" will be used to refer to the transducing of an image into a signal and "read" to refer to the transducing of a signal into an image. For linear nutation (for linear motion blur) a point on the write image corresponds to two bracketing points on the read image or vice versa. Similarly, for circular nutation (for defocus or diffraction blur) a point on the write image corresponds to a circle on the read image or vice versa. Linear nutation is accomplished by the superimposition of two displaced images, while circular nutation may be two ways -- either by

(1) the superimposition of multiple images displaced in a circular locus, or

(2) scanning a circle in the write image for every point in the read image or vice versa.

The capabilities of various input read and write systems were explored:

2.2.1.5.1. Light-emitting diode arrays. These arrays are imaged on a transparency and the entire transparency is imaged on a photoreceptor. Nutation consists of sequencing the array elements to generate a signal. In the case of linear nutation, the array elements would be sequenced in successive rows. The shift is achieved by omitting a column or columns of elements to the left and then to the right. The number of columns omitted determines the degree of shift.

In the case of circular nutation, the arrays are sequenced in approximations of circles. The resultant signal generated by the photoreceptor is analog with respect to amplitude, but digital with respect to the discrete number of data points sampled. The sequencing speed is relatively slow and the number of array elements to scan a given frame impose other limitations on this approach.

2.2.1.5.2. Photo-diode arrays. A transparency is imaged on a photo-diode array. Nutation is accomplished by the same sequencing procedures just described. The same limitations of LED arrays also apply to photo-diode arrays.

2.2.1.5.3. Fiber optics. A standard fiber optic bundle can scan an image by moving across in lines. The separation of the lines is equal to the diameter of the bundle. For linear nutation there is a displacement of the bundle in one plane relative to the other. For circular nutation one end of the bundle moves orthogonally while the other moves in a spiral, which is akin to continuous circular movement with a continuous displacement of the center.

Circular nutation can also be achieved by a specially designed bundle consisting of an annulus of fibers, moving across the original image. The other end would emit the light into a photoreceptor to result in both nutating and transducing the original image into a signal.

In all cases, mechanical movement of the fiber optic bundle is necessary, with the attendant mechanical problems, slow speeds and the engineering of new equipment.

2.2.1.5.4. Flying spot scanners. These, where available, are mostly geared for the speeds required for digitizing the signal. The scanner is versatile and can be programmed to either scan in circles or scan a series of displaced images. The scanners investigated, however, are not readily available and are costly.

2.2.1.5.5. Video cameras. Nutation capability in a video camera is limited by the destructive nature of its writing. As the electron beam moves across the charged plate, the voltage in the scanning trail is discharged, so that nutation cannot be performed by writing overlapping circles. However, nutation can be achieved by writing a field of contiguous circles, allowing sufficient time for regeneration of the voltage and returning for the next field, etc. Or, the camera can scan a series of displaced frames to perform a nutation.

2.2.1.5.5.1. image dissector cameras. These, where available, lack the resolution of vidicon cameras and are costly.

2.2.1.5.5.2. vidicon cameras. These are readily available, some have high resolution, high bandwidth, high signal-to-noise ratios and choices of line and frame rates.

2.2.1.5.6. Scan conversion memories. The heart of this device is a cathode ray tube with a charge-storage target rather than a phosphor screen. The target has memory properties and integrates images by adding successive frames. Nutation is achieved by the electron beam scanning a circle for each point scanned by the input device (a video camera, for instance). It can also accomplish nutation by integrating a series of image frames displaced in a circular locus. In the case of linear motion blur, it can integrate two images displaced from one another.

2.2.2. Amplification

Weighting or amplification, as described in the Interim Report, refers to a proportional scaling of the illuminance values of an image.

Weighting can be accomplished photographically by increasing or decreasing the exposure. However, the H & D curve of photographic emulsions is not linear. The greatest departure from linearity takes place at the shoulder and toe of the curve. Therefore, photographic scaling is not proportional for all illuminances in an image and the criterion for amplification is unfulfilled. This was demonstrated in the experiments mentioned in 2.2.1.2. of this section.

Weighting as a computer processing subroutine is entirely feasible and proved successful in the feasibility experiment mentioned in 2.2.1.4. of this section.

2.2.3. Subtraction

Subtracting one image from another is an integral step. True subtraction by photographic methods does not appear possible. The experiments mentioned in 2.2.1.2. of this section included a simulation of subtraction by filtering a projected image through a transparency. This is actually a multiplication by a variable factor of less than one. The filtering yielded a small improvement in resolution but fell far short of a true subtraction as performed in the computer.

Computer subtraction is no problem at all and was successful in the feasibility experiment mentioned in 2.2.1.4. of this section.

Electronic subtraction is simply accomplished by reversing the polarity of the signal of the subtrahend image and combining it with the signal of the minuend. Other electronic subtraction techniques are equally effective and will be discussed later.

2.3 GENERAL DESIGN CONSIDERATIONS

It is apparent that any electronic system could best meet the goals of this program by operating on a maximum of information from the image to be processed. Digitizing the information, while preserving the integrity of the digitized values, places an ipso facto limit to the information to be processed and imposes a further limit on the processing speed. Present state-of-art limits are 8 bits per picture element and 40 MHz conversion rates, so that exclusive of processing time, analog to digital conversion and back to analog would take 16 seconds for a 2000x2000 array. A completely analog system became a principal design aim.

2.3.1. Input

The input device is required to function as an optical to electronic image transducer, capable of translating an optical image into an analog signal, retaining information relative to the illuminance and spatial orientation of picture elements. The distortions occurring in such a device, which must be minimized, may be optical or electronic. Some limits are imposed by the resolution of the optical system which focuses the image onto a plane where the electronic translation is performed. The electronic translation itself is subject to the limits of the dynamic range, the resolution capability, the stability and duration of storage and the stability, linearity, geometry and width of the scanning electron beam. The sum total of these distortions and/or limitations must be negligible as compared with the degree of resolution improvement to be achieved by the processing. For this reason, the input device requires optical and electronic elements of the highest quality and greatest versatility. After a survey of the available devices and their state of the art and consideration of all the trade-offs, it became obvious that the input would be a video camera.

The video signal of a television camera is generated by the discharge of voltages from the camera tube. This discharge takes place as an electron beam sweeps across the face of the tube. The beam sweeps in response to deflection voltages at the neck of the tube. At zero voltage, the beam is directed at the center of the tube. In order for the beam to begin a sweep at the left of the tube, a negative deflection voltage is applied. As the negative voltage is decreased the beam sweeps toward the center where there is zero voltage. The deflection current then changes to a positive voltage so as to continue the sweep to the right of the tube. The oscilloscope trace of this voltage shows an ascending line from left to right. At the height of ascent, the line drops almost vertically when the current changes from positive to negative. This is the phase when the beam retraces to begin the next line. The oscilloscope trace of these deflection signals are the ramps which will be discussed in the material that follows.

The camera can perform the functions necessary for linear nutation quite well. An offset voltage can be applied to the ramp signal, which places a bias on the horizontal sweeps. This bias can effectively shift a frame to the left or right so that the combination of the two shifts achieves a linear nutation.

However, for circular nutation, the destructiveness of the camera beam precludes a spiral-like nutation of overlapping circles. Contiguous circles were rejected as being needlessly complex to generate. The scanning of successive frames displaced in a circular locus fails to use all the available information by averaging a finite number of data points instead of integrating an entire circle. Therefore the camera functions as an optical-electronic transducer and performs linear but not circular nutation.

2.3.2. Memory

The method selected for circularly nutating an image requires the integration of overlapping circular scans of image point ensembles. Processing for motion blur includes the integration of image points from two or more shift positions. Both techniques require a memory; in the first case to store the scanned circles and to provide the capability of adding them successively as they are scanned, so as to produce the resultant integral value; in the second case to record and retain the first frame until the second frame is scanned and added.

As detailed in the Interim Report, weighting or scaling a frame is one of the techniques employed. The memory device serves as a storage for the addition of successive frames. Subtraction is another technique employed. A memory is necessary to store one frame of video information until the frame to be subtracted has been processed and is ready for the subtraction.

Two types of memory systems were considered -- a scan conversion memory and a video disc recorder. The disc recorder serves well as a straight-forward memory device. Options are available for adding or subtracting frames. These options make it possible for the disc recorder to integrate information, but it must be done in an indirect manner. Since the signal is frequency modulated before recording, it is saturated, so to speak, so that once recorded it may not be altered by addition or subtraction. The options enable the playback of one particular frame so that the signal may be combined with that of another frame and the combination re-recorded for playback on a monitor. It is also possible, with separate video channels, to playback two frames, mix them and re-record. This playback and re-record may introduce resolution losses in the system, so that this method of frame integration is best avoided, if possible.

The scan conversion memory, on the other hand, has direct integration capabilities. Within the limits required by processing of this project, images may be directly added to one another by increasing the charge on the target. The scan conversion memory also has the capability to selectively erase. Therefore the electron beam, while in the erase mode, can be modulated by the video signal of the frame to be subtracted, so that a true subtraction takes place. This technique must not be confused with that of polarity reversal for subtraction. If the polarity of the subtrahend signal is reversed and it is added to the minuend signal, the target will merely integrate positive charges. This would not result in the subtraction that is attained by mixing the signal of the polarity reversed subtrahend with that of the minuend. Therefore, the selective erase technique appears to be the most promising for subtraction.

Another object of a memory device is to play back two frames for comparison. These might be an unprocessed frame and its processed counterpart or two frames processed with different parameters. A disc recorder has the storage capacity for a library of such frames, easily accessible for playback, whereas a scan converter can only store one frame at a time.

2.3.3. Function Generation

The conventional video system is based on broadcast television standards. There are 525 lines per frame and 30 frames are scanned in one second. The standard 2:1 interlace scanning pattern begins by deflecting the electron beam to scan from left to right across the top line of the image. Then the beam is blanked while it retraces to skip a line and scan the next, etc. This is generally referred to as an orthogonal interlaced scan. The ramp signals which deflect the beam to perform this scan usually originate in the camera from an internal ramp generator.

The processing techniques employed by this project require unconventional scans which are provided by external generators. For processing linear motion it is necessary to displace frames. This displacement can be achieved by introducing either a delay or an offset voltage in the ramp signal that controls the x-axis deflection plates. Cameras are available with adjustments to provide an offset voltage.

For processing defocus or diffraction blur, a circular nutation is necessary. This requires that either the camera or the scan converter scan a circle corresponding to each point that the other scans. Since nutating with the camera beam has been precluded, it is necessary to nutate in the scan converter. Function generators can furnish deflection signals which are basically sine waves, square waves, triangular waves and combinations of these. A deflection signal to scan a circle may be produced by generating a sine wave for the x deflection plates and another sine wave for the y plates, but these must be 90° out of phase with one another. This type of signal can be produced by a function generator to provide a sine wave and a phase lock generator to replicate the sine wave and lock the original and replicated waves 90° out of phase.

Since the camera scans orthogonally, one may consider each line to be a moving picture element. Therefore the scan converter scanning pattern must be a constantly repeating circle whose center moves along a line corresponding to the scanning line of the camera. The position of the center of the scanning circle along the line that it traverses in the scan converter must correspond with the position of the moving picture element along the scanning line in the camera at any point in time. The defelction signals of the camera and the scan converter are, then, not the same. However, the position of the electron beam on the camera raster and the locus of the center of the repeating circle on the scan converter target must correspond in time and space. This can be accomplished by generating two signals. An external ramp generator supplies the deflection to the camera. The same signal is also supplied to a modulating circuit. The modulating circuit combines the signal from the phase-lock generator with that from the ramp generator and the modulated signal drives the scan converter.

2.3.4. Resolution

The original information to be processed is contained in a transparency. This information is transmitted by providing a bed of illuminance to form an image (the "object" in the optical sense). The first task, then, is to provide a bed of illuminance which is as near uniform as possible. The light box chosen for this project can limit variations in illuminance to less than 1%.

The axis of the camera must be as nearly perpendicular to the plane of the transparency as possible. The stand procured to contain the light box and camera maintains a perpendicular relationship between the two components to within ±5 minutes of arc.

The resolution of the lens system of the camera must be at least equal to that of the electronic system itself. The transparencies generated for this project were, for the most part, produced by a 35 mm camera, as were those for the experiments previously mentioned. These experiments revealed that the resolution of certain Nikkor lenses exceeded 75 line pairs per mm. This project employs electronic components with a resolution of up to 2100 lines per raster. If the image to be processed is a 35 mm transparency, the shorter dimension is 24 mm and the resolution requirement of the camera is then some 42 line pairs per mm, well within the capacity of available lens systems for the video camera.

Some general considerations of resolution apply to each of the electronic components. For the purposes of this report, horizontal resolution will be considered the resolution of vertical lines of an image and vertical resolution that of horizontal lines. In the general consideration of video systems with an orthogonal scan, the ultimate limit to resolution is the diameter of the scanning spot. Therefore, the vertical resolution is certainly limited by the number of scanning lines in the raster. The horizontal resolution, however, is bandwidth limited.

2.3.4.1. 2000-Line Systems

In a 2000-line raster at a frame rate of 30/sec, each frame is scanned in 33,333 μs and each line in 16.67 μs. Deducting the retrace time of 7 μs, the active line time is 9.67 μs. If the bandwidth of the camera is 30 MHz, the number of picture elements per line is (9.67/.033) or 290. The limiting resolution of the 1.5 inch vidicon camera tube used for this project is 1600 TV lines per picture height. If the aspect ratio of the raster is 4:3, then the maximum number of elements per line is 2132. However, a 30 MHz bandwidth camera limits this to 290, about 1/7 of the tube's limit. It is possible to increase the number of picture elements up to the tube's resolution limit by merely slowing the frame rate. In the case cited above, a slowdown from 30 to 4 frames per second can accomplish this. Ramp generators are available which can vary the frame rate continuously from 10 microseconds to 10 seconds per frame, so that the limiting resolution of the tube can be attained.

In the case of the camera, the ramps of an external generator are not ordinarily compatible with the deflection amplifier of the camera. However, there are magnetic deflection generators available which, when interfaced with the camera, allow the camera to accept external commands. The systems design includes such a magnetic deflection generator interfaced between the ramp generator and the camera.

The scan converter, however, will accept externally generated ramps. The same considerations of trading off time for resolution also apply to the scan converter, as its bandwidth is the same as that of the camera. The scan converter has a further time limitation. The deflection amplifier has a bandwidth of 700 kHz. Working with a 2000x2000 array of picture elements, 4,000,000 circles have to be written in the scan converter, which can write at a rate of 700,000 per second. This limits the nutating speed to about 7.14 seconds per frame. Higher bandwidth deflection amplifiers can be engineered for special applications and are being considered.

The video disc recorder bandwidth is 6.5 MHz, but is limited to standard TV rates of 525 lines, 30 frames/sec.

Final evaluation and comparison of images are made by the human visual system viewing video monitors. A survey of high resolution monitors revealed the availability of 2000+ line models with bandwidths exceeding 30 MHz. The resolution of 290 picture elements per scanning line imposed by bandwidth on the camera, also applies to the monitor. These monitors are ordinarily limited to 30 frames per second but can be modified to accept slower scans to overcome the resolution limitation. However, at slower scan rates, the fading time of the phosphor presents a problem to the viewer. The critical flicker frequency of the normal human eye is about 20 under normal illumination. It is defined as the rate of presentation of intermittent, alternate discontinuous photic stimuli that just gives rise to a fully uniform and continuous sensation obliterating the flicker (syn., critical fusion frequency, fusion frequency, fusion flicker frequency, flicker fusion threshold). For direct viewing of the monitor, the resolution of the final display is limited by the bandwidth of the monitor. A modification of the monitor will make it possible to photograph the slower scan displays so that the horizontal resolution of the photographs will exceed 2000 picture elements per line instead of the 290 by direct viewing. The development of monitors with slower fading phosphors is considered beyond the scope of this program.

2.3.4.2. <u>Other Line Rates</u>

The same calculations used for the 2000-line system apply to other line rates. All the components are sufficiently versatile to operate in 195 line rates from 289 to 2100 lines per raster. The line rate mode may not be related to the resolution improvement capabilities of the system. The principal advantage of higher line rates is the capacity to process larger areas of an image. The factors that determine the optimum area of the image to be processed include:

(1) the amount and nature of the blur,

(2) the dynamic range of the original image,

(3) the grain size and distribution in the emulsion,

(4) the thickness of the emulsion, and

(5) the capability of the electronic system to deblur a particular degradation.

2.4. FUNCTIONAL DESIGN CONSIDERATIONS

2.4.1. Linear Motion Blur Processing

2.4.1.1. One Cycle

One cycle of processing for linear motion blur consists of the following steps:

(1) small shift linear nutation,

(2) amplification of the small shift nutation,

(3) large shift linear nutation, and

(4) subtraction of the large shift nutation from the amplified small shift nutation.

Each linear nutation consists of the following steps:

(1) a shift of the original image n picture elements to the left,

(2) a shift of the original image n picture elements to the right, and

(3) the addition of these two shifted images.

The shifting can be accomplished by an offset voltage applied to the x deflection plates of the camera or the scan converters. The addition of the images may take place in either of the scan converters or in the video disc recorder; both capabilities have been provided. The video signals may be amplified either by the camera or by either scan converter. The amplification may also be accomplished by integrating more frames in the scan converter, and the video amplitude of this sum can also be controlled by the diaphragm setting of the camera lens system.

The subtraction may be made in either scan converter or in the video disc recorder. Both components have this capability.

2.4.1.2. Two or More Cycles

The second cycle consists of the same procedures as the first, except that the final image of the first cycle serves as the image to be nutated. Two-cycle processing may be accomplished two ways.

2.4.1.2.1. Separation of cycles. The first cycle is performed as described above, with the final image formed in one of the scan converters. An offset voltage is applied to the x-axis deflection plates of this scan converter in the read mode, and the shifted image is written on the other scan converter. A second frame, shifted an equal amount in the opposite direction, is written over (added to) the first shift in the second scan converter.

The difference between the first and second cycles is that the camera performs the shifting in the first cycle and the scan converter in the second. This is true of both the small and large shifts in the second cycle. The amplification of the small shift linear nutation may not necessarily be performed by the camera since the transfers in the second cycle are from scan converter to scan converter. The subtraction, as in the first cycle, may take place either in the second scan converter or in the video disc recorder.

If there are three or more cycles, the procedure is the same as in the second cycle -- from scan converter to scan converter. There is one principal objection to this procedure. The transfers from component to component result in degradations.

2.4.1.2.2. Combination of cycles. The resultant image at the end of the first cycle is really a combination of four weighted images derived from the original. The resultant image at the end of the second cycle is a combination of four weighted images derived from the resultant image of the first cycle. The second resultant image is then really a combination of 16 weighted images derived from the original.

Therefore, after determination of the parameters, the camera may horizontally shift the original image 16 times, each shift amplified where required, and then added or subtracted in either one of the scan converters or the video disc recorder. Three cycles of processing, if productive, require 64 shifts, amplification where required, and the appropriate additions and subtractions to compile the final image.

The separation of cycles technique requires a total of 8 shifts, 4 additions and 2 subtractions for two cycles of processing. This is as opposed to 16 shifts, 7 additions and 8 subtractions for the combination of cycles technique. For two-cycle processing, the former technique involves the processing of an already processed image and transfers from camera to scan converter to scan converter, while the latter requires transfers from camera to one scan converter.

2.4.2. Circular Processing

2.4.2.1. Circular Nutation -- Technique #1

The circular nutation is performed by the scan converter, whose electron beam can be programmed to write a continual circle, the center of which moves in a conventional orthogonal video scanning pattern. The frame rate limitation imposed by the bandwidth of the deflection amplifier has been mentioned as being limited to 7.14 seconds for a 2000-line system. If the signal that is being nutated originates in the camera, the camera, then, must be slowed to this frame rate. This raises another problem. When the camera scans slower than one frame per second, the charges on the electronic image plate of the camera begin to spread, impairing resolution.

A subsystem has been designed to provide the circular nutation. A ramp generator generates slow scan ramp signals which go to the magnetic deflection generator to drive the camera. A function generator produces a sine wave which goes to a phase-lock generator. This, in turn, replicates the sine wave and locks the replicated and original waves 90° out of phase. The signal from the phase-lock generator goes to a modulator to be mixed with the ramps generating the sawtooth for the camera. This composite signal then generates the circular scan in the scan converter.

2.4.2.2. Circular Nutation -- Technique #2

There is, however, another approach. The original image may be conventionally read from the camera and conventionally written in one scan converter. This scan converter then performs a conventional orthogonal scan in the read mode and the second scan converter performs the spiral or circular scan in the write mode. However, some resolution loss is anticipated as a result of the extra transfer.

This technique requires a different functional subsystem. The camera is driven in the same manner. The signal from the ramp generator also drives the first scan converter, so that the camera and scan converter are driven by the same ramps. This will result in the recording of the original signal in the first scan converter.

The ramp generator then generates a signal to the first scan converter containing the transferred original image, so that it is scanned orthogonally in the read mode. The signal from the ramp generator also goes to the modulator, where it is combined with the signal from the phase-lock generator. This composite signal then drives the second scan converter, where the circular nutation is performed by the spiral scan in the write mode.

There is a variation on technique #2 where the spiral scan is performed by the first scan converter and the orthogonal by the second. This requires that the first scan converter receive the composite signal from the mixer and that the second receive the conventional ramps directly from the ramp generator.

In a 525-line system, the bandwidth of the deflection amplifier limits the frame rate to .53 seconds per frame. There is no danger of resolution loss due to charge spread in slowing the camera to this frame rate. The basic advantage of technique #1 is one less transfer and, since there is no appreciable charge spread in the camera at this frame rate, technique #1 is indicated for lower line rates.

2.4.3. Defocus Blur Processing

2.4.3.1. One Cycle

One cycle of processing for defocus blur consists of the following steps:

(1) small radius circular nutation,

(2) amplification of the small radius circular nutation,

(3) large radius circular nutation, and

(4) subtraction of the large radius circular nutation from the amplified small radius circular nutation.

Circular nutation itself has already been discussed. The other steps are accomplished by the same techniques and with the same functional design as described for one cycle of linear motion blur processing.

2.4.3.2. Two or More Cycles

The second cycle consists of the same procedures as the first, except that the final image of the first cycle serves as the image to be nutated.

2.4.3.2.1. Separation of cycles. The first cycle is performed as above. The final first-cycle image is on one of the scan converters. This image is then processed using either variation of technique #2. Both the techniques and the functional design of the system are the same as those required for technique #2. The sole difference is that the image to be processed is the first-cycle resultant image instead of the transferred original image.

2.4.3.2.2. Combination of cycles. Either technique #1 or #2 may be employed for this processing. The same trade-off considerations previously discussed also apply here. The resultant image at the end of the first cycle is a combination of two weighted nutated images derived from the combination of the two weighted nutated images of the first cycle. Each nutation of the second cycle, then, may be broken down as (1) a nutation of a nutation, (2) weighting, (3) a nutation of a nutation, and (4) subtraction.

For two-cycle processing, both the separation and combination techniques require the combination of four frames. However, the separation technique employs the processing of a processed image, while the combination only processes the original image. But, the combination technique requires the generation of a much more complex deflection signal with extra black boxes. At present, the functional design of the subsystem includes the capability for the separation technique. The combination technique is beyond the scope of the present design.

2.4.4. Diffraction Blur Processing

One cycle of processing for diffraction blur consists of the following steps:

(1) circular nutation,

(2) amplification of the circular nutation, and

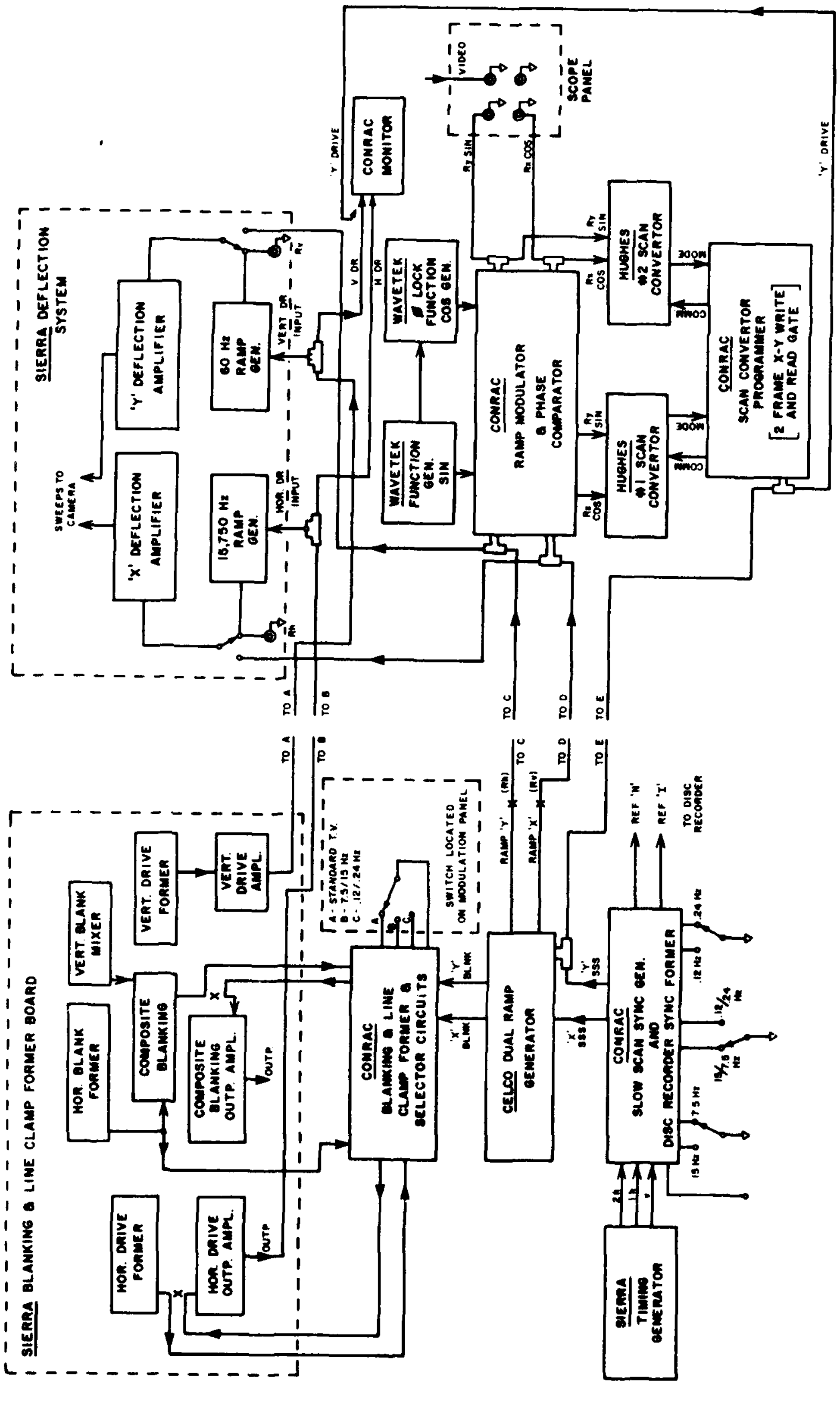
(3) subtraction of this amplified image from the original image.

All the same processing alternatives and trade-offs discussed for defocus blur processing apply to diffraction blur processing. The functional design of the system requires no further modification.

3. *FINAL DESIGN*

3.1. INTRODUCTION

Figure 4 is a comprehensive block diagram of the system. A second copy of Fig. 1 is included for ease of reference in this section. It shows the finished system with the various components and controls numbered.



Figs. 4.1 & 4.2 System schematic

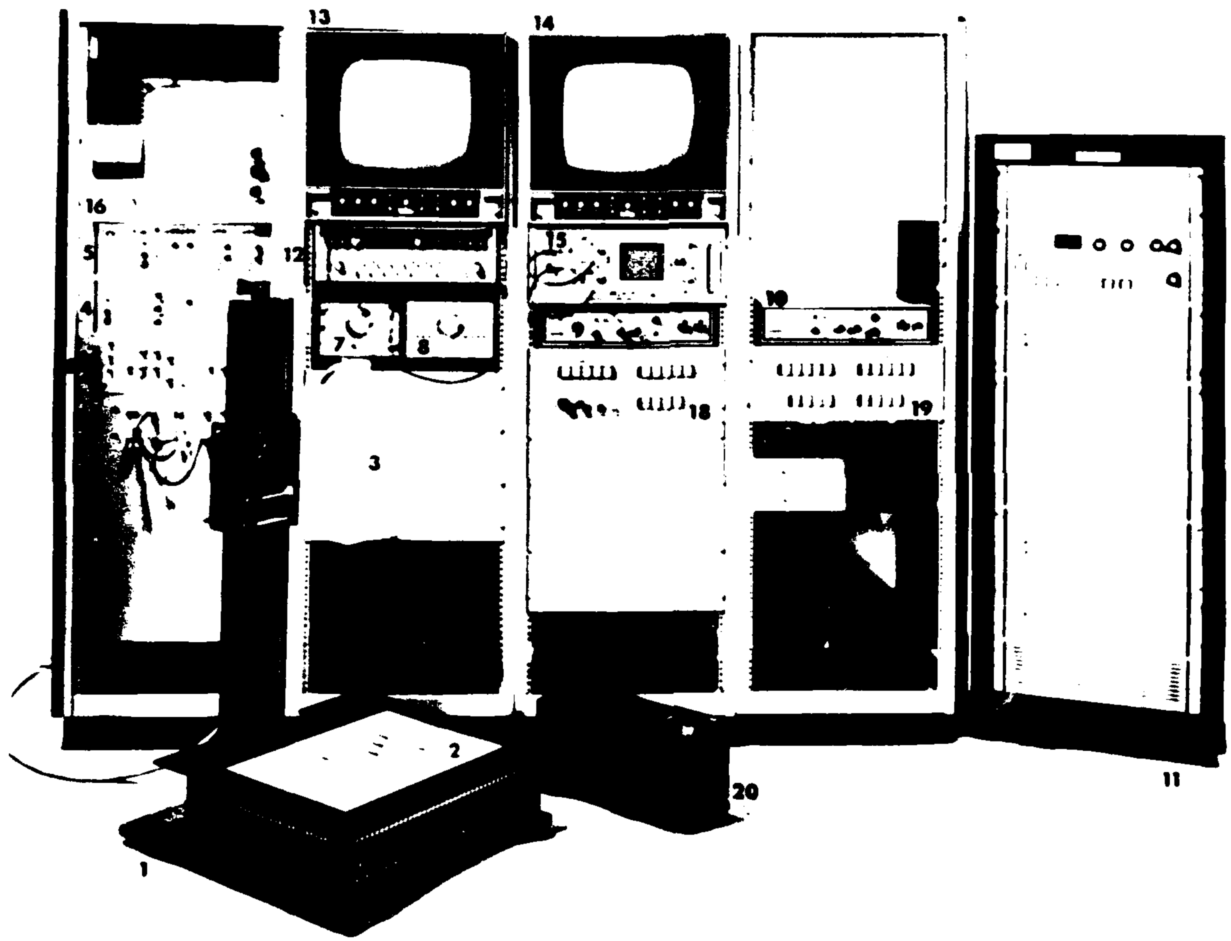


Fig. 1. Prototype image processing system.

3.2. INPUT

The primary input for the system is a vidicon camera (see Appendix C). The camera control unit is shown as Component No. 4 in Fig. 1 and the camera head is no. 3. There are two heads, one designed for conventional TV rates (525 lines, 30 frames/second) and the other for slower scan rates and higher line rates. This camera was procured for its versatility of line rates (from 289 to 2100 lines per raster), its high signal-to-noise ratio (40 db) and its high resolution (1600 picture elements per line).

A magnetic deflection generator (see Appendix C) was supplied for the camera. This generator interfaces with other components so as to enable the camera to scan at non-standard rates. It is shown as component 5 in Fig. 1.

The camera also has a deflection control for offsetting the scan along the x axis. This control is used for horizontal linear shifting, in processing an image for motion blur.

The camera is mounted on an instrument stand, component 1 of Fig. 1. It looks at a transparency on the light box, component 2 of Fig. 1. The light box is designed for no greater than $\pm 2\%$ difference in illuminance throughout its surface. The light box power supply is shown as component 20 in Fig. 1.

3.3. DEFLECTION

In standard TV rates, the deflection is provided by internal ramp generators in the camera. In non-standard rates, the deflection is provided by a 2-channel ramp generator (see Appendix C), designated as component 6 in Fig. 1. This generator supplies vertical ramps with sweep times which may be varied from 10 μsec to 10 sec and horizontal ramps in the range from 10 μsec to 100 msec.

Circular nutation is achieved by modulating the ramps with a circular scan. It is formed by two function generators (see Appendix C). The first generator, designated as component 7 in Fig. 1, outputs a sine wave and the second generator, designated as component 8 of Fig. 1, replicates the sine wave 90° out of phase and locks the two wave forms to form a circle (Fig. 5.1). When this circle modulates one scanning line, the result is the spiral wave form shown in Fig. 5.2. Fig. 5.3 shows the generation of a 9-line raster in the osciloscope. These function generators do not limit the system in frequency.

The ramps are modulated by the circles in a modulation circuit designed for the system. The controls are shown in panel 16

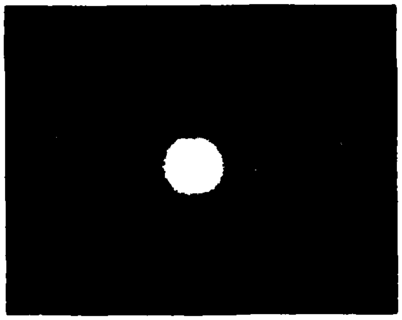


Fig. 5.1. Oscilloscope display of circular scan.

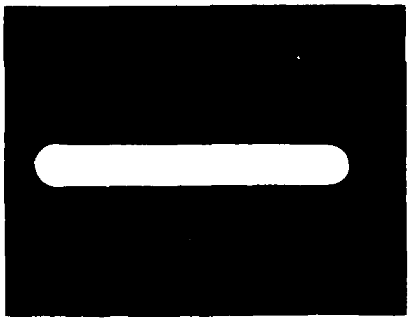


Fig. 5.2. Oscilloscope display of one circular scan line.

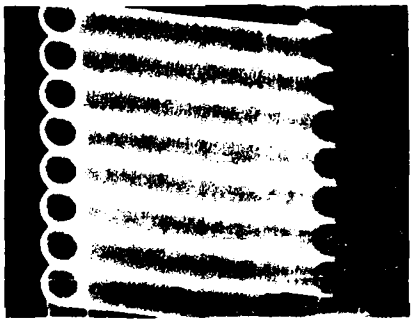


Fig. 5.3. Oscilloscope display of a circular scan line raster.

of Fig. 1. These consist of a selector switch so as to provide unmodulated ramps or to nutate in either one or the other scan converter. There are also two amplitude potentiometers which determine the radius of the circle, one for the x and the other for the y axis.

3.4. Timing

The synch pulses that provide the basic timing for the system originate in the camera's internal synch generator. The slow scan timing is provided by a synch counter which forms the basic synch pulses from the camera synch generator, so that the slow scan rates of the system are multiples of the basic 525 line 30 frames/second standard TV rates. The composite synch signal consists of the vertical and horizontal synch pulses for any given rate. These pulses provide the triggering for both the ramps and the blanking.

3.5. BLANKING

The blanking inactivates the scanning electron beam during the retrace cycles during both the line and the field retrace. At standard TV rates the blanking is provided by the blanking generator of the camera. Special circuitry was designed for slow scan blanking. Both the timing and blanking circuitry are located behind the modulation panel (Fig. 1, no. 16). The controls to switch timing and blanking rates are on the front of the modulation panel.

3.6. RATES

Five rates were arbitrarily selected for operation of the system:

(1) 525 lines; 30 frames/second; 2:1 interlace.

(2) 1050 lines; 15 frames/second; 1:1 interlace.

(3) 2100 lines; 7.5 frames/second; 1:1 interlace.

(4) 1050 lines; .23 frames/second; 1:1 interlace.

(5) 2100 lines; .12 frames/second; 1:1 interlace.

3.7. MEMORY DEVICES

3.7.1. Scan Converters

The system contains two scan converters (see Appendix C), designated components 9 and 10 in Fig. 1. The purpose of the second scan converter was to provide an input memory for the output of the first scan converter. This is necessary for reprocessing an image that has already been processed in the first scan converter. In this case, the image in the first scan converter is functionally the primary image and the second scan converter is available for processing this image.

Each of the two scan converters has the capability of image offset -- one for standard TV rates and the other for the remaining rates. When reading an image from one scan converter to write in the other, either image or both may be displaced during the transfer.

The ramps of either scan converter may be modulated by the circular scan of the function generators so as to perform a nutation. In this case, the sweeps of the read image (from the camera or one scan converter) are conventional, while the sweeps of the write image are modulated. When a scan converter image is the input, this process may be reversed, but if the camera is the input, the output scan converter sweeps must be modulated. This is because the camera beam is destructive and as the circular scan involves overlapping of successive circles, the video information at the intersections is wiped out.

Both scan converters also have three types of erase capabilities. When an image is stored in the scan converter, it can be completely erased by discharging the electrical charge on the face of the tube. It may also be partially erased by partially discharging the electrical charge. The scan converters also have another operational mode called "selective erase". In this mode the erase beam is modulated. If the erase beam is modulated by a video signal from an image, it effectively subtracts the image that modulates its beam. Therefore, if an image is already stored in a scan converter, one can subtract another image from the stored image by writing over the stored image in the selective erase mode. The selective erase beam is controlled by a gain so that the subtracted image can be weighted relative to the stored image.

The circuitry of both scan converters provide for scanning at any of the operational rates of the system. Processing takes place when:

(1) images successively displaced in two or more positions in the camera or one scan converter are integrated in a scan converter, or when

(2) an image from the camera or one scan converter is read orthogonally (with unmodulated ramps) and nutated (circularly scanned with modulated ramps) as it is written in the other scan converter, or when

(3) the input scan converter is in the selective erase mode.

3.7.2. Video Disc Recorder

The video disc recorder (see Appendix C) is contained in the rack shown as component 11 in Fig. 1. The disc file has a capacity of 600 fields or 300 frames and only operates at standard TV rates. There are two stepping heads for the recording or playing back of any frame, one head for each field. There are seven recording or playback rates from 1 to 30 frames per second.

In addition, there are two fixed heads for the recording or playback of one frame. This frame may serve as the subtrahend in a subtraction circuit. The disc recorder can also subtract a video frame input from another component. The subtraction may be made from any tracks accessible to the stepping heads. The images in the subtraction may be weighted by a balance control which weights the minuend and subtrahend in any proportion from all minuend no subtrahend through equal minuend and subtrahend (zero video image level) down to all negative subtrahend and no minuend. The output of the subtract network may not be directly recorded back in the disc recorder since all four available heads are participating in the subtraction. The result may, however, be indirectly recorded by inputting the subtraction image in one of the scan converters and then reading this image back into the disc recorder. The gray level and resolution losses in transfer make this procedure inadvisable.

3.8. OUTPUT DEVICES

3.8.1. Monitors

Two high resolution monitors (see Appendix C) are shown as components 13 and 14 in Fig. 1. Each has two interchangeable tubes -- one for standard TV rates and the other for slower rates. The standard tubes contain P4 phosphor and serve well only at standard rates. The slow scan tubes contain P39 phosphor and serve well at standard rates (30 frames/second) down to the 15 frames/second rate where there is some flicker. The persistence of the phosphor at 7.5 frames/second is insufficient and results in an annoying flicker. The monitors can handle the limiting resolution of the primary camera image, which is 1600 picture elements/line, 2100 lines/raster.

Each monitor has two channels. The height and width of the image may be adjusted for each channel so that quick changes in magnification may be made by clicking from one channel to another for better appreciation of some images.

3.8.2. Oscilloscope

The oscilloscope (see Appendix C) is shown as component 15 of Fig. 1. It has two channels for display and four nearby bulkhead connectors. Two of these are connected to the modulator for the display of the vertical and horizontal ramps; each of the others are connected to the monitors for the display of the respective video signals. The scope is indispensable for adjustint scanning rates and various camera levels. It is also necessary for trouble shooting the entire system.

3.9. IMAGE ANALYSIS

The image analyzer (see Appendix C) is shown as component 12 in Fig. 1. It has a number of capabilities which are useful in processing. One of these is level slicing so that an image may be broken down to anywhere between two and ten brightness levels. It also provides for the relative measurement of image point brightness by moving horizontal and vertical cursors to intersect at the point in question. The digital readout displays values in a scale from 1 to 1000. There is also area measurement capability.

The analyzer can constitute an isometric projection of an image so that the apparent viewing angle can be altered by adjusting a dial. This portion of its circuitry requires an xy monitor output which is not available to the system. The oscilloscope may be used but the resolution is poor. The image analyzer also has color analysis and synthesis capacities which are not applicable to this system.

3.10. SELECTION PANELS

3.10.1. Signal Modes

The signal mode patch panel is shown as component 17 of Fig. 1. This panel provides for recabling necessary when changing to and from standard TV rates. There are three functions requiring these changes:

(1) camera vertical drive,

(2) monitor vertical drive,

(3) blanking.

3.10.2. Component Interfacing

The component input selector buttons are shown in panel 19 and part of panel 18 in Fig. 1. The input and output video signals of all components are cabled into a distribution amplifier. The video signal is channeled through this amplifier from one component to another. Each video component, except for the camera, has its own group of input buttons. Selection of the appropriate button determines the flow path of the video signal from one component to another through the distribution amplifier.

3.10.3. Scan Converter Controls

In addition to the controls on the front panels of the scan converters, panel 18 of Fig. 1 shows the mode and command controls for the scan converters. Three controls are used for all scanning rates. These are:

(1) prime,

(2) erase, and

(3) selective erase.

There is one control for each scan converter which activates the TV write command. This is used in standard rates. At all other rates the control for xy rates is an enabling button. The activation of the command is accomplished by another control while the enabling button is depressed.

There are also viewing mode controls, one for each scan converter. These are necessary at the slower rates. After a command is executed, the scan converter automatically reads the image into the monitor at 30 frames/second. The monitor, however, may be operating at either 7.5 or 15 frames/second. In this case, the viewing mode control changes the vertical rate of the scan converter to match that of the monitor.

4. *PROCESSING*

4.1. LINEAR

4.1.1. Method

4.1.1.1. Nutation

Linear processing involves 3 steps:

(1) small shift or nutation,

(2) large shift or nutation, and

(3) weighting and subtraction.

In linear nutation the function generators may modulate the ramps so as to repeatedly move the scanning beam from side to side during the sweep of each ramp. The radius control of the x axis on the modulation panel is set at the desired level and the y axis control is set at 0. This has the effect of collapsing the y axis of the scanning circle, turning the circle into a line. This results in the production of a horizontal line in the nutated image for each point in the degraded image.

The other method for linear nutation was described in the Interim Report. This consists of first linearly shifting the entire scan in one direction and storing the shifted image in memory. Second, the image is linearly shifted in the opposite direction and added to the first image already in memory. This results in the superimposition of two displaced images and the production of two points in the "nutated" image for each point in the original image. Both methods achieve the same objective.

Scanning a line for each point requires the use of a scan converter since the modulator only outputs to either of the scan converters. Further, the prototype system described here has been designed for the modulator to operate only at slower than standard TV rates, which limits the processing speed.

Displacement of the image can be accomplished by the additional deflection control of the camera or the position control of either of the scan converters. The camera and one of the scan converters can displace an image in standard TV rates and the camera and other scan converter can perform the displacement in other rates, so there is no scanning rate limitation in linear shifting.

The small shift is accomplished by the integration of two shifted images in the scan converter. The displacements are then increased for the large shift. The write gains on the scan converters require a more sensitive adjustment than for linear nutation because of the necessity for integrating two images to a critical voltage.

4.1.1.2. Subtraction

4.1.1.2.1. Scan converter. The subtraction may be made in the scan converters. Using linear nutation, the dimension of the x-axis of the collapsed circle is first set for the small nutation on the modulation panel and the image is written into memory of one of the scan converters. The dimension of the x-axis is then increased for the large nutation and, as this image is scanned, it is selectively erased from the image already in memory. The scan converter write gain must be adjusted so that the brightest points on the first image are just short of tube saturation. The selective erase gain must then be adjusted so as to selectively erase just half the voltage of the large nutation image from that of the small. This turned out to be a rather lengthy trial and error procedure. Further, it was discovered that there is some displacement of the selective erase image relative to the stored image. This resulted in a resolution loss in the processed image.

4.1.1.2.2. Disc recorder. The subtraction may also be made in the disc recorder. Either linear nutation or image shifting may be employed. In the case of linear nutation, the small nutation is first written in one scan converter at slower than standard TV rates, since these rates are limited by the modulation circuitry. The large nutation is then written in the other scan converter. Since the disc recorder only operates at standard TV rates, the system requires the appropriate changes of settings to standard rates. The small nutation image is then read from one scan converter onto one of the numbered tracks of the disc recorder and the large nutation image onto the fixed track. The subtraction network of the disc recorder is then employed and the optimum weighting of the images for subtraction is easily accomplished by turning the balance knob while observing the monitor output.

In the case of linear shifting, the system may be set up for standard TV rates, thereby avoiding rate changes during the processing. The small and large shift images are each integrated on a scan converter, transferred to the disc recorder and subtracted in the same manner as already described.

The use of the disc recorder has certain other advantages, both in processing time and quality of processing.

(1) Weighting the selective erase image in successive trials in the scan converter is unnecessary. Changing the weighting is performed continuously by turning the subtraction balance knob in the disc recorder.

(2) There is no perceptible displacement of the images while participating in the subtraction, so that optimum resolution is maintained.

(3) The image processed in the disc recorder is less noisy than that of the scan converter.

4.1.2. Image Transfers

Degradations resulting from image transfers between scan converters are pronounced. Fig. 6 shows a video resolution target. Fig. 7.1 is a sector of a 525-line camera-to-monitor image of this target. Fig. 7.2 is an image of the sector at standard rates, where the camera image was written in the scan converter and read on the monitor. Fig. 7.3 shows the result of a second transfer, where the image shown in Fig. 7.2 was read from one scan converter into the other and the stored image read into the monitor. Fig. 7.4 is the image of a third transfer, where the image shown in Fig. 7.3 was read from the second scan converter and written in the first scan converter and is displayed on the monitor. A comparison of Figs. 7.1 - 7.4 shows the successive contrast and resolution loss with each transfer.

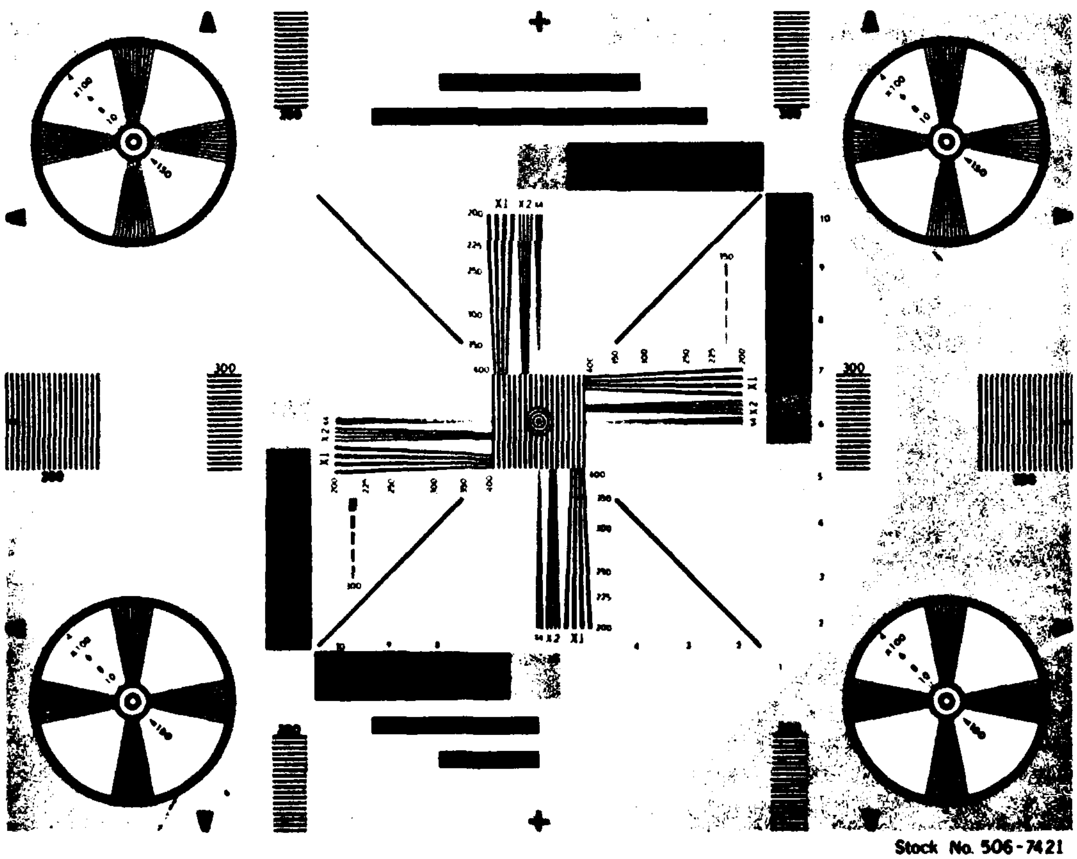


Figure 6. Video resolution target.

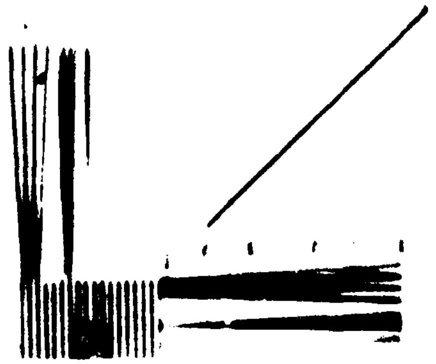


Fig. 7.1. Video resolution target -- 525-line camera image.

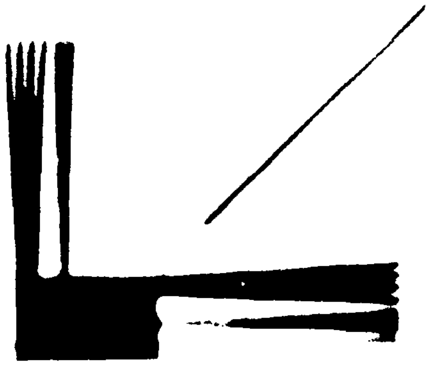


Fig. 7.2. Video resolution target -- 525-line scan converter image -- 1 transfer.

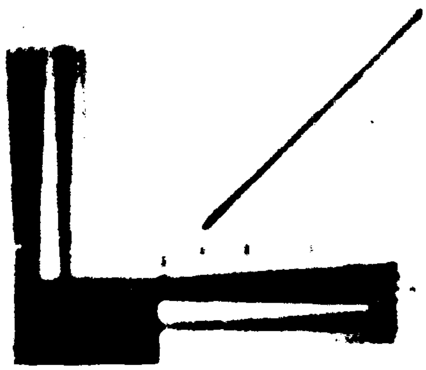


Fig. 7.3. Video resolution target -- 525-line scan converter image -- 2 transfers.

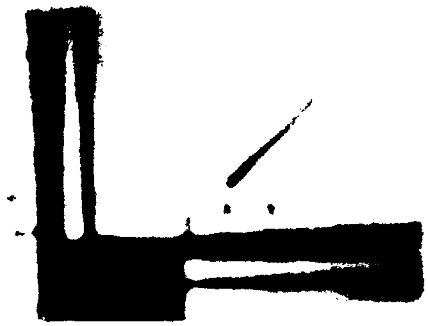


Fig. 7.4. Video resolution target -- 525-line scan converter image-- 3 transfers.

These figures point up the importance of avoiding transfers, where possible.

One of the features of the disc recorder is the ability to subtract an input image from a stored image. This avoids the transfer of the image before subtraction.

4.1.3. Processing Results

4.1.3.1. <u>Air Force Resolution Target</u>

Fig. 8 is an image of the Air Force resolution target. Fig. 9.1 is a motion blurred image of this target. It is one of the images produced by the procedure described in Appendix B. This image was processed by linear shifting. The camera raster was offset to produce the displacements. The integration of two smaller displacements in the scan converter is shown in Fig. 9.2. This image was transferred to the fixed track in the disc recorder. The integration of two larger displacements in the scan

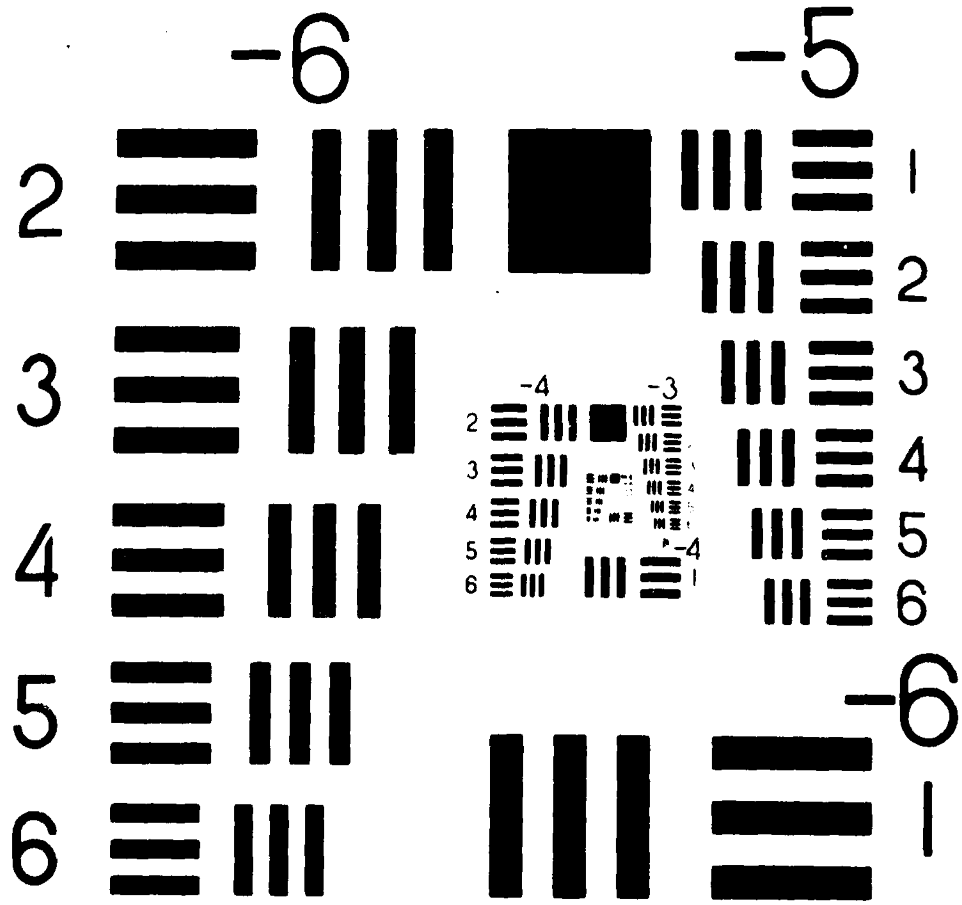


Figure 8. Air Force resolution target.

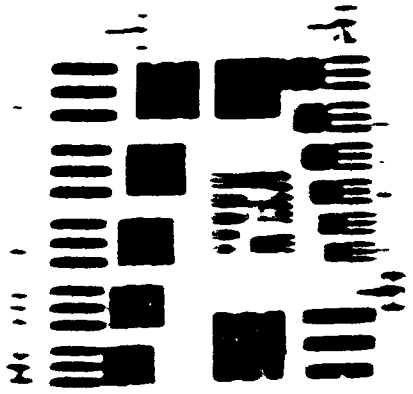


Fig. 9.1. Air Force resolution target -- motion blurred image.

Fig. 9.2. Air Force resolution target -- motion blurred image -- small nutation.

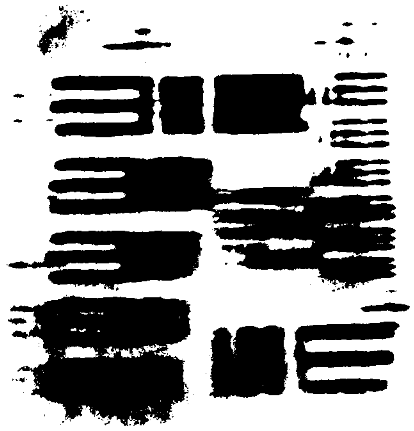


Fig. 9.3. Air Force resolution target -- motion blurred image -- large nutation.

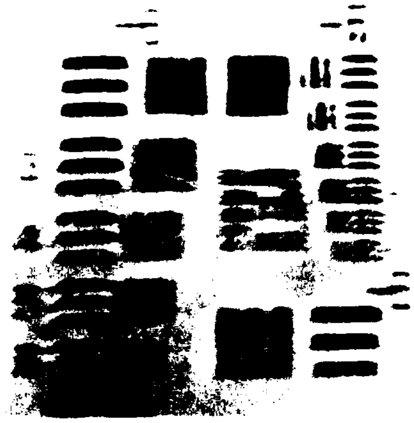


Fig. 9.4. Air Force resolution target -- motion blurred image -- subtraction.

converter is shown in Fig. 9.3. This image was then input to the disc recorder where it was subtracted from the fixed track image. The result of the subtraction is shown in Fig. 9.4.

Fig. 9.1 shows resolution of elements 1 and 2 of group -6. Element 3 is almost a zero crossing (referring to the first spatial frequency of zero contrast in an optical transfer function of motion blur). From here to element 3 of group -5, there is a phase reversal with spurious resolution. There is probably another zero crossing somewhere between elements 3 and 4 of group -5, followed by another phase reversal of the next group of smaller elements.

Fig. 9.2 shows a loss of resolution in elements 1 and 2 of group -6 which were resolved in Fig. 9.1. Element 3 shows some resolution, while elements 4-6 of group -6 and 1-3 of group -5 show a phase correction. Fig. 9.3 shows a phase reversal of elements 1 and 2 of group -6 and a phase "doubling" of the next smaller group of elements. Then this image was subtracted from that of Fig. 9.2; the resultant processed image is shown in Fig. 9.4. With the exception of element 3 of group -6 where there was near zero contrast, all the elements down to group -5 element 3 are shown resolved, about 110 percent improvement in resolution.

4.1.3.2. Moving Truck

Vehicles in motion were photographed to produce motion blurred images for processing. Two simultaneous exposures were

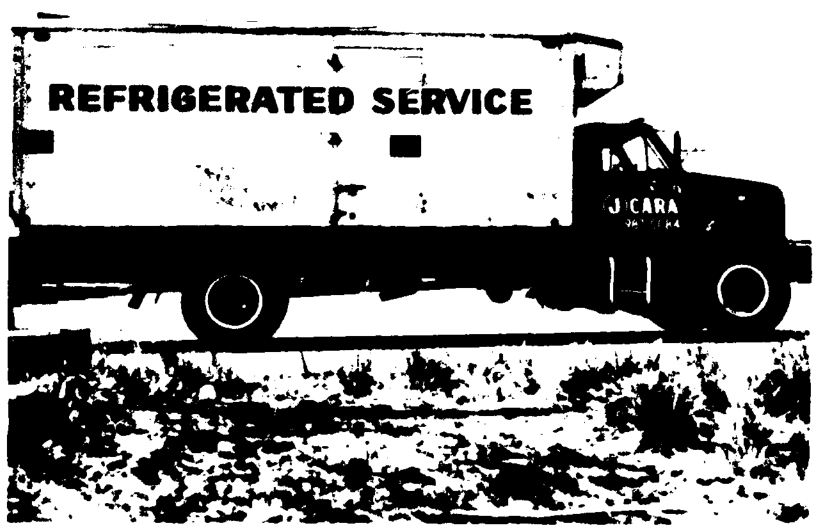


Figure 10.1. Moving truck -- short exposure.

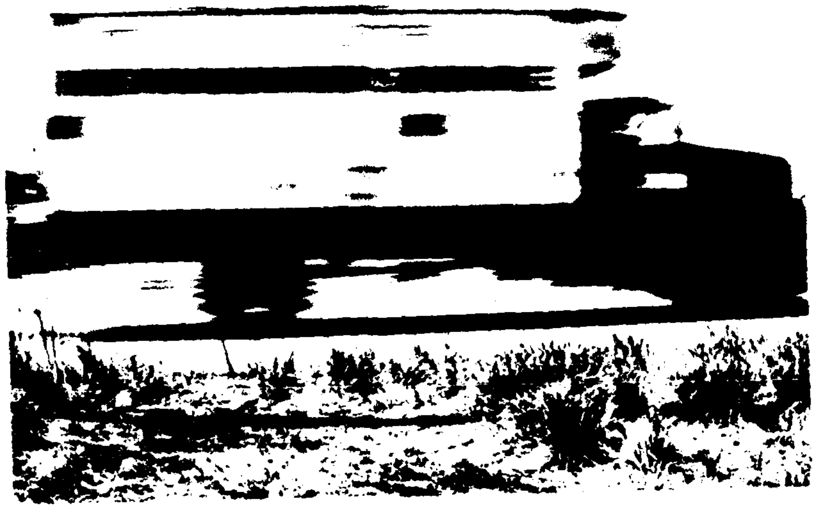


Figure 10.2. Moving truck -- motion blurred exposure.

Figure 10.3. Moving truck -- motion blurred -- processed.

made at different shutter speeds. Referring to Appendix A, set-up 1 was employed for the slower shutter speed depicting the motion blur and set-up 3 for the faster speed to provide a reference image.

Fig. 10.1 is the rapid exposure image of a moving truck where the motion blur is minimized and the smaller detail is resolved. Fig. 10.2 is the slower exposure image showing the resulting motion blur. This image was processed in the same manner as the resolution target, as described in the previous section. The processed image is shown in Fig. 10.3. The appreciation of the alphanumerics is heightened by adjusting the viewing distance of the observer. Only limited improvement is achieved, indicating further experimentation is needed in this area.

4.2. CIRCULAR

4.2.1. Method

Circular processing requires the same three steps as in linear processing:

(1) small radius nutation,

(2) large radius nutation, and

(3) subtraction.

The circular nutation is accomplished by modulation of the deflection signals so as to superimpose the circular scan on the normal ramps. Therefore, while the scanning beam in the camera reads the image in a conventional orthogonal scan, the writing beam in the scan converter is modulated to store a nutated image.

There are two bandwidths in the scan converter to be considered. One is that of the video signal which is 30 MHz and the other is that of the deflection amplifier, which is 700 KHz. This limits the number of circles that can be written in 1 second. This is the reason for the slow scan speeds of 4.267 seconds per frame for a 1050-line raster and 8.533 seconds per frame for a 2100-line raster.

4.2.1.1. Very Slow Scan

Slow scan introduces other problems. First, there is some spread of the electron beam at these rates so that resolution is impaired. Second, the linearity of the response is affected so that the dynamic range of the gray scale is limited. Third, the focus differs at different rates. Some of these problems are amenable to adjustment. These adjustments may not be made while viewing the monitor, since the monitor has a limited frequency range and, further, the persistence of the phosphor is just long enough for a field rate of 15 frames/second. The image must be slow scanned into the scan converter at the 4.267 sec/frame rate (for instance). Then, the system must be reset for a viewing rate of 15 frames/second so that the scan converter can read the image into the monitor for viewing. An adjustment may then be made and the process repeated. There are two static focus controls and five dynamic focus controls on the camera. The same considerations are true of the scan converter, and the same number of potentiometers also require adjusting. There is also an interrelationship between some of the controls so that after each has been optimized in turn, the earlier adjustments require re-optimization and the process must be repeated with both the camera and scan converter. Further, these components are not completely stable so that readjustment is necessary from time to time. At best, there is both a serious resolution impairment and dynamic range loss at the very slow scan rates.

4.2.1.2. Slow Scan

The nutation can also be accomplished at the 15 frame/second rate, with the bandwidth problem mentioned earlier. This may be performed in two ways.

(1) A 1050-line image is read by the camera and stored in the scan converter at 15 frames/second employing conventional deflection. This image is then read with a circular scan so that the monitor displays a nutated image. This method provides the capability of observing the image as the radius of nutation is changed so as to optimize the resolution. However, since the disc recorder only operates at standard rates and the circular scan is only available at the 15 or 7.5 frame/second rate, the nutated image can not be transferred to the disc recorder by this method.

(2) Once the x and y axes parameters have been determined by the first method, the 1050-line image is then rescanned by the camera orthogonally and written in the scan converter circularly at 15 frames/second. This results in a stored image that has been processed by circular nutation. The system settings are then changed to standard rates and the image transferred to the disc recorder.

Despite the resolution limits imposed by the deflection amplifier of the scan converter at the 15 frame/second rate, the overall result proved superior to that achieved at the very slow rates, because of the other problems already discussed.

The subtraction was made in the disc recorder for the same reasons discussed in Section 4.1.1.2.

4.2.2. Processing Results

A series of defocused images of the Air Force resolution target (Fig. 8) was produced as described in Section 1.2.1.1. The image selected for processing was exposed with the camera focused for a distance of 2 ft. 9 in. and a target-film plane separation of 10 ft. It is shown in Fig. 11.1. The image was circularly scanned at 15 frames/second as described in the preceding section. Fig. 11.2 shows the small radius nutated image and 11.3 the large. Fig. 11.4 shows a display of the subtraction performed in the disc recorder about 50 percent improvement in resolution.

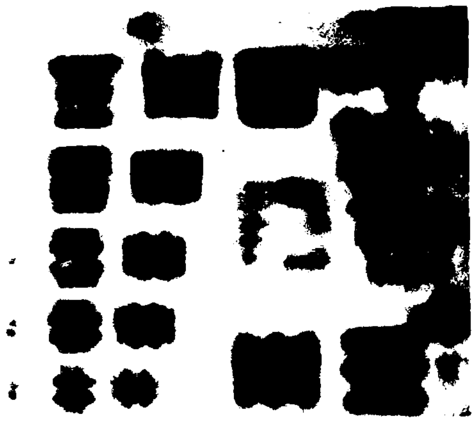


Fig. 11.1. Air Force resolution target -- defocused image.

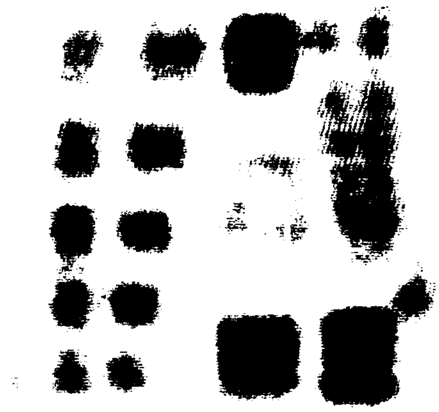


Fig. 11.2. Air Force resolution target -- defocused image -- small nutation.

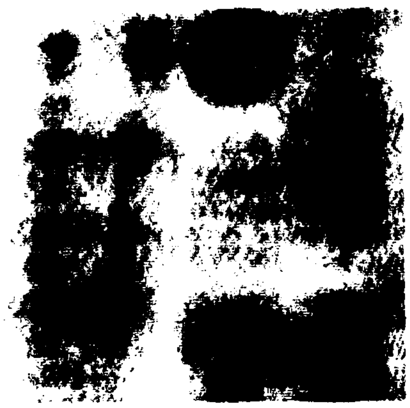


Fig. 11.3. Air Force resolution target -- defocused image -- large nutation.

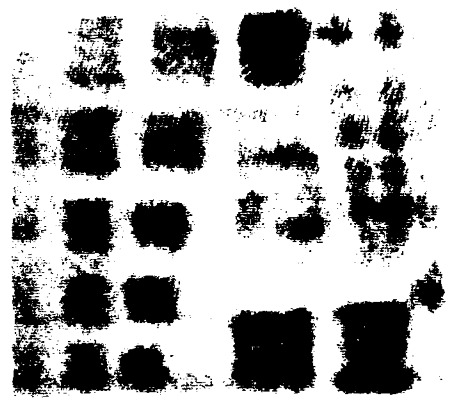


Fig. 11.4. Air Force resolution target -- defocused image -- subtraction.

5. RECOMMENDATIONS

There are a few areas for improvement in the prototype system as presently designed. These include:

5.1. INITIAL SCAN

The vidicon camera presents certain limitations. The circuitry is unstable and various adjustments are necessary from time to time. Some of these are too sensitive to be logged in so that results are not fully repeatable. Furthermore, since many of the camera adjustments are interdependent, a large amount of time is consumed in maintaining stability.

The vidicon camera beam is destructive and time is required for regeneration of the image charge before the beam can read the same area of the tube face. This precludes circular nutation by the camera as the points of overlap of adjacent circles are erased. For reasons that will be examined in Section 5.2, the nutation should ideally be performed at the read level of the original image, which really precludes the vidicon camera.

For these reasons it is recommended that the state of the art of primary image reading devices be studied for the selection of a camera replacement component that meets the following general specifications:

(1) high resolution -- up to 2100 lines

(2) bandwidth of at least 30 MHz -- both video and deflection

(3) signal-to-noise ratio of at least 30 db

(4) good linearity

(5) stability

(6) non-destructive reading

(7) a. the capability of continuously varying line rates, or

b. the capability of accepting externally generated ramps which are continuously variable.

In the event that the ramps are generated externally, a variable blanking generator must be integrated into the system so that the line and field rates may be continuously varied from the standard TV rates to the system's highest resolution.

Therefore, it is recommended that the vidicon camera be replaced by a new "front end" for the system.

5.2. INTERMEDIATE STORAGE

One of the greatest problems of the present system is the increase in noise and loss of resolution with each image manipulation and transfer. The greatest contributor to this problem is the intermediate storage device, which, in this case, is the scan converter. The slow rates were made necessary by the bandwidth limitation of the deflection amplifier of the scan converter. The scan converters could be eliminated from the system if the primary reading device had a nutation capability. The nutated image could then be written directly into the disc recorder. This would result in a considerable resolution improvement and less noise by the elimination of two transfers. The elimination of the scan converters would also provide for higher processing speeds at standard TV rates. Further, all the internal scan converter potentiometer adjustments required when changing rates would no longer be necessary.

5.3. VIDEO DISC RECORDER

With the changes recommended in 5.1. and 5.2., the video disc recorder would serve a dual purpose. First it would participate in the processing by using its subtraction network as at present, and would be a repository for processed images for later comparison. However, in order to accomplish this, some modifications would be necessary.

(1) At present, the subtraction network produces an output which can be viewed on the monitor. This output cannot be stored because both pairs of heads are participating in the subtraction. A third pair of heads is necessary to store this output, which is really the processed image, for later retrieval. The third pair would also be fixed track heads. The present stepping heads would then be used to record the output of the subtraction by the two pairs of fixed heads and later to retrieve any of the processed images in the disc file.

(2) An addition network will also be required. First, where linear shifting is employed, it is necessary to integrate the two or more shift positions of an image. Second, where two cycles of circular processing are productive, it will also be necessary to integrate nutated frames.

The disc recorder as presently designed does have the capability of polarity reversal of the output. It may be possible to use this circuitry selectively in combination with the subtraction network so as to subtract a negative image, which would effectively perform the integration. This is a matter for the disc recorder manufacturer to resolve.

(3) The possibility of revision of the disc recorder for the purpose of storing high resolution images should also be explored. There are three basic problems involved. First, the video bandwidth of the disc recorder is limited to about 6 MHz. Therefore, higher resolution images require slower rates to maintain resolution in the disc recorder. If the "front end" of the system were designed to operate at slower rates, it would require multiple tracks to store an image. The second problem is that the present disc recorder design limits its capability to standard TV rates. Its synch circuitry would require redesign so as to accept slower rates to be written on multiple tracks. The controller would also require modification so as to start and stop at a designated rate.

The third problem is that if multiple tracks are necessary for a single image, the present pair of fixed heads and the recommended second pair of fixed heads would have to be steppers, and track addresses would have to be assigned for the use of each pair of heads -- a limited number for one frame for each pair of heads participating in the addition or subtraction, and the balance of the addresses for the storage and later retrieval of processed frames.

5.4. MULTIPLE CYCLES

It was originally anticipated that a processed frame could be reprocessed in a second cycle by further nutation. The recommended changes make this impossible as the processed frame is video information on a track or tracks of a disc.

However, a nutation of a nutation can be performed by nutating in epicircles, or, in this case, epicircular spirals. A series of these can then be combined by addition and subtraction in the disc recorder so as to effect the result of two conventional cycles of processing. Epicircular nutation can be accomplished by the addition of two more function generators. However, this raises the problem of bandwidth limitations. Even at the present state-of-the-art 30 MHz bandwidths of reading components, considerably slower line and field rates will be necessary to achieve optimum resolution. Since slow rates are a problem for the video disc recorder, the slow scan modification requirements as set forth in 5.3 will be necessary before epicircular nutation can be considered.

5.5. CONTROLLER

The multiplicity of adjustments required to process one image with one set of parameters has been described at length. Even if the recommended changes are effected, a great deal of time will be required to process an image. Except for the fraction of a second required for the actual processing, the rest of the time will be spent in changing settings, modes, addresses and switching. It is recommended that the entire system be automated by a controller. This controller will effect all connections and modes, generate the appropriate voltages necessary at different settings and determine the sequence of processing. It can iterate the processing with changing parameter. A series of images processed by different parameters can be quickly stored in the disc file for side by side comparison on the monitors at the conclusion of the iteration cycle determined by the program of the controller. This provision should simplify the processing so that a technician can operate the device with a minimum of orientation. This can provide a valuable tool for use in the field.

APPENDIX A

PHOTOGRAPHY EQUIPMENT AND MATERIALS

1. Equipment Components

1.1 Nikon F2 Camera Body
1.2 Lenses
1.2.1 50-300 mm f/4.5 Zoom-Nikkor Auto Lens
1.2.2 50 mm f/2 Nikkor H Auto Lens
1.2.3 55 mm f/3.5 Micro-Nikkor-P Auto Lens
1.2.4 105 mm f/4 Bellows-Nikkor Lens
1.3 89B Infrared Filter
1.4 Tripod
1.5 Nikon "K" rings, nos. 1-5
1.6 Nikon Bellows Attachment PB-4
1.7 Cable Release
1.8 Nikon Motor Drive
1.9 Cordless Battery Pack

2. Materials

2.1 Films
2.1.1 Kodak High Contrast Copy Film
2.1.2 Kodak High Speed Infrared Film
2.1.3 Kodak Panatomic X Film
2.2 Developers
2.2.1 Kodak D-19
2.2.2 Simple Pota Process Developer

Graphadone "A"	1.42 g
Sodium Sulfite, des.	28.40 g
Water, to make	1 qt

2.2.3 Kodak HC 110

APPENDIX B

LINEARLY MOTION-BLURRED IMAGES

The motion table, its timing and controls are shown in Fig. 12. The numbers designate the following:

1. voltmeter
2. variable transformer
3. stop-clock (1-60 sec; increments of 0.01 sec)
4. motion table control unit containing
   a. on-off switch
   b. direction switch
   c. potentiometer for velocity control
5. reflective scanner and support

6. amplifier
7. table
8. servo motor and drive
9. table framework

The following determinations were made:

1. the longest traverse distance at which the motion table reached peak velocity, using incremental potentiometer settings through the full range;

2. average peak velocities using 10 samplings at each of these settings, and

3. the standard deviation at each setting.

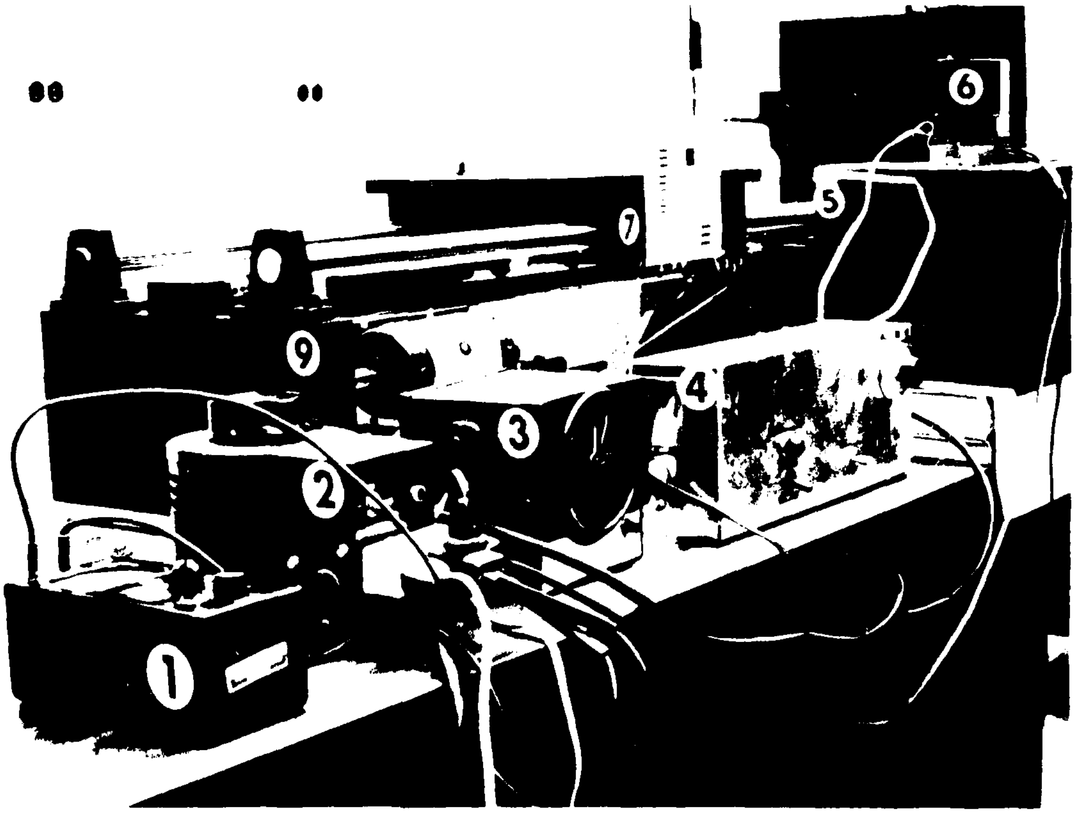


Figure 12. Motion table and associated components.

The velocity at the smallest standard deviation was selected, together with a series of six shutter speeds at intervals of 1 f/stop. Six Air Force resolution targets were produced according to the dimensions calculated from these data. They algebraically varied in size by a factor of $\sqrt[6]{2}$ so as to produce a series of six blur lengths when photographed in motion. Each blur length corresponded to each element in a particular group. Therefore, with each selected shutter speed calculated for the blur length range of a particular group, an exposure was made of each target. This resulted in the production of a series of 36 linearly motion blurred images, each showing a different element at a first zero crossing.

APPENDIX C

ELECTRONIC COMPONENTS

1. Camera

manufacturer:	Sierra Scientific Corp.
model:	1.5" vidicon camera, model LSV-1.5R(032A)
subcomponents:	camera head with standard scan tube
	camera head with slow scan tube
	camera control unit
	magnetic deflection generator
	decentering control
	camera stand
	light-box
	power supply for light box

2. Ramp Generator

manufacturer:	Constantine Engineering Laboratories Co.
model:	R-G 116 dual axis ramp generator

3. Function Generators

manufacturer:	Wavetech, Inc.
models:	116 function generator
	132 VCG noise generator

4. Scan Converters

manufacturer:	Hughes Aircraft Co.
	Industrial Products Div.
model:	639 VHR scan conversion memory
options:	02C external read -DC restore;
	external XY writing;
	09 package configuration on front panel;
	zoom controls are 2 linear potentiometers

5. Video Disc Recorder

manufacturer:	Data Disc, Inc.
model:	2012487-00 video disc recording system
subcomponents:	3302V single channel 3600 rpm 300 frame video

	disc recorder;
	servo drive
	crystal card
options:	controller
	subtraction network
	buffer track

6. <u>Monitors</u>
   manufacturer: Conrac Corporation
   model: RQB 17/R solid state high resolution monitor

7. <u>Oscilloscope</u>
   manufacturer: Tektronix, Inc.
   model: R465 oscilloscope

8. <u>'mage Analyzer</u>
   manufacturer: Interpretation Systems, Inc.
   model: VP-8 image analyzer

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